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Fuzzy thermoeconomic optimisation applied to a small waste water treatment plant

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ABSTRACT

This work proposes to use thermodynamic modelling, and fuzzy thermoeconomic to optimise the small waste water treatment plant work period concerning to sewage treatment and energy generation through products associated to it. Thermoeconomic optimisation is described as a fuzzy non-linear programming problem in those local criteria is multi-objective: maximum exergetic efficiency and minimal total cost rate. These objective functions and constraints for this non-linear programming problem can be structured and represented by fuzzy sets. Several simulations about real possibilities are done to search the best performance configuration for the small waste water treatment plant. Results deal to previous system optimisation that was a physical optimisation through a thermo-economic analysis. Then, Pareto set for this one indicated that the system had been optimised previously and it is working with better configuration.

Contents

1. Introduction

A small waste water treatment plant (SWWTP) has several products associated to sewage treated in it. The small waste water treatment plant at Sao Paulo State University, campus of Guaratingueta, in its original design, has a fat box, three anaerobic reactors, one aerobic–anoxic reactor, a gas holder, a H_2S filter, an internal combustion engine, and three heat exchangers to warm sewage in anaerobic reactors, improving micro-organisms colony growing. Also are produced water for re-use, biofertilizer, and biogas, and is generated electrical power. These products are directly dependant of sewage amount that becomes from administration building and cafeteria. Figs. 1–3 show the small waste water treatment plant and its components. Fig. 4 shows the process diagram with flows and fluids detached.

The waste water from administration and cafeteria buildings (Fig. 2) enters through primary solids filter. This preliminary treatment eliminates the rudest solids, such as fat blocks.

The waste water follows through three up-flow sludge blanket anaerobic bioreactors, which separate solid residues (sludge), biogas, and waste water (preliminary treatment) through a helical phase flow. In this stage, part of the sludge is removed and used as biofertilizer. Another part is maintained because micro-organisms present in there, predominantly of *Methanosaeta* gender [5], digest organic material present in sludge to produce biogas. In Fig. 4 is possible to see heat exchangers associated to each anaerobic bioreactor. This is to maintain internal temperature in 37 °C, which is ideal for the micro-organisms presented in there [5]. This biogas is transferred to a gas holder, where it is stored at an appropriated

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Fig. 1. Small waste water treatment plant (back view) [1–4].

Fig. 2. Small waste water treatment plant (front view) [1–4]].

Fig. 3. Small waste water treatment plant (water wheel) [1–4].

pressure for engine feeding, responsible for the generation of sufficient power energy to maintain associated small energy systems such as a control room, illumination, a pump etc.

The waste water flows until a fourth bioreactor (aerobic–anoxic), where aerobic micro-organisms digest any organic material that was not digested by anaerobic organisms, besides transforming ammoniacal nitrogen in nitrate. Anoxic micro-organisms transform nitrate in gaseous nitrogen and remove part of phosphorous in sludge bacterial biomass form. At that stage, treated water falls on a water wheel and generates mechanical power as well as air for aerobic bacteria treatment. This reusable water may be used in green areas ferti-irrigation.

A sort of anaerobic and aerobic bioreactors characteristics were obtained by [5–9], such as typical values for low power value of urban residues, biomass, and biogas, waste water treatment condition in Brazil, comparison between different bioreactors types, power generation and biogas production features, among others.

Focus on alternative energy sources has provided new modelling techniques, more accuracy of generating systems, allowing for a more rigorous and clear technical–economical analysis. As an example exergoeconomic and thermoeconomic analysis models have been used as a powerful tool for energy systems optimisation. Exergetic production cost (EPC) is a new method developed for the analysis and optimisation design of thermal systems. The objective of this technique is the minimum (optimal) total operating costs of a plant assuming a constant rate of production and electrical power generation [1,3,4,10–15].

Thermoeconomics is today a powerful tool for studying and optimising an energy generation system. The application of this technique is important for the evaluation of utility costs as products or supplies of production plants, energy costs between process operations or of an energy transformation system. These costs may be applied in viability studies, in investment decisions, by comparing alternative techniques and operating conditions, in a cost-effective evaluation of the equipment during installation, in an exchange or expansion of an energy system [10,12,13,15].

Several works based on the development of methodologies to model and to optimise thermal energy systems have been analysed in order to obtain information about techniques used in these evaluations [16–38].

Development of models for thermoeconomic design and operation optimisation has also been evaluated. These models deal with thermoeconomic optimisation and the best way to obtain balance between exergy balance and energy production/generation costs [39–53].

Thermoeconomics has been presented in several works relating exergy balance analysis and costs minimisation. These works have played an important role for the establishment of basic fundamentals issues necessary for the development of the proposed methodology [54–70].

The waste water treatment has been considered as a viable generator of an alternative fuel, biogas, according to the sewage treated and techniques used [71–73]. Methane is the main component of biogas generated by anaerobic waste water treatment and it is about 21 times more harmful than carbonic dioxide as related to greenhouse effect [7]. The use of biogas is very interesting, mainly when associated to renewable energy generation concepts and environmental protection.

Artificial intelligence techniques have been used to help analysis, mainly based on decision making, i.e., genetic algorithm, neural networks, rough sets, fuzzy logic, and others.

Mazur [74] had presented a work that achieves to include an uncertainty into classic thermoeconomic analysis in order to find solutions that simultaneously satisfy thermodynamic and economic goals, where thermoeconomic optimisation had been considered as a

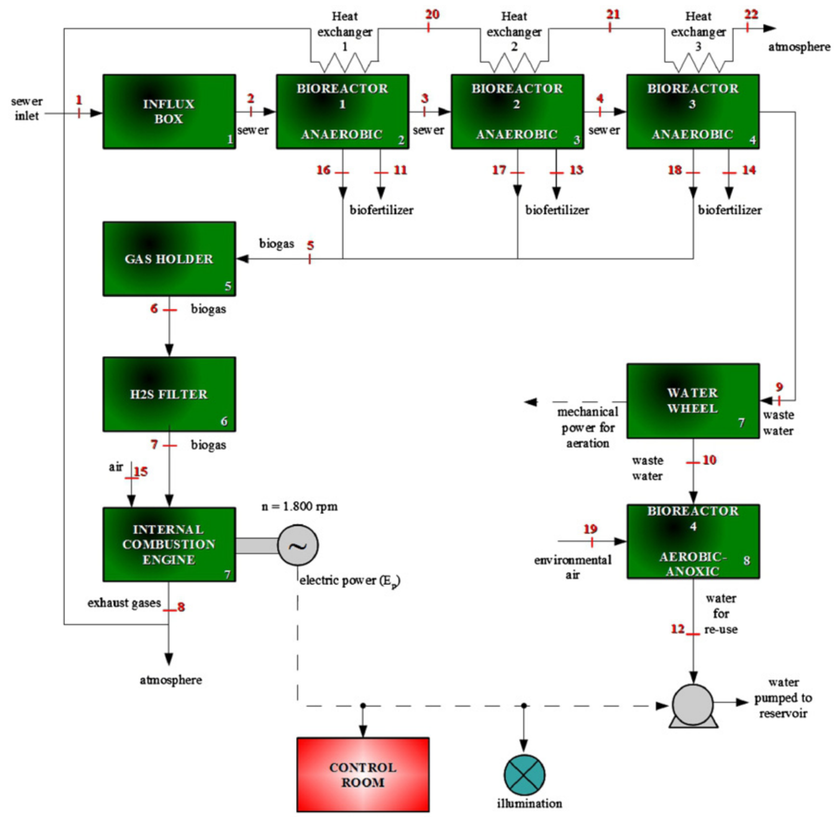

Fig. 4. Process diagram [1,3,4].

fuzzy non-linear programming problem where local criteria: maximum energy (exergy) efficiency and minimum total cost rate as well as different constraints in an ill-structured situation can be represented by fuzzy sets. Mazur [75] also had developed a new approach for thermoeconomic analysis of energy-transforming systems based on the sequential uncertainty account to make decisions that simultaneously meet thermodynamic and economic goals.

Toffolo and Lazzaretto [76] had suggested how to perform a multi-objective optimisation in order to find solutions that simultaneously satisfy exergetic and economic objectives. Also a multi-objective optimisation for design of a benchmark cogeneration system known as CGAM cogeneration system was performed by [77,78]. A multi-objective optimisation with self-adaptive algorithm was developed by [79]. Fuzzy logic features associated to multi-objective optimisation for decision making issues was evaluated by [80]. Evolutionary algorithm features was associated to multi-objective optimisation by [81].

Das and Dennis [82–85] had proposed methods for Pareto optimal points evaluation for general non-linear multi criteria optimisation problem, with multi-objective features.

This work is a step forward of [3,4], also connected to [1], and proposes to use thermodynamic modelling, and fuzzy thermoeconomic to optimise the small waste water treatment plant work period concerning to sewage treatment and energy generation through products associated to it.

2. Methodology

Thermoeconomic optimisation is described as a fuzzy non-linear programming problem in those local criteria is multi-objective: maximum exergetic efficiency and minimal total cost rate. These objective functions and constraints for this non-linear programming problem can be structured and represented by fuzzy sets. Several simulations about real possibilities are done to search the best performance configuration for the small waste water treatment plant.

The original SWWTP design anticipate 70 m^3 of sewage diary with a mass flow of 4.28 kg/s, which flows for three anaerobic bioreactors with the same capacity of sewage storage and treatment, but generating different fractions of nominal 24 Nm^3/day of biogas (mass flow of 1.47 kg/s), which are transferred to system gas holder. This gas holder sends the biogas to a motor-generator set with nominal capacity of 5.5 kW for diesel and 4 kW for biogas, working 10 h a day, feeding control room and illumination system. There is a fourth bioreactor, aerobic, that treats waste water before its transferring to anoxic purification stage for a final treatment stage. Biofertilizer can be obtained from both anaerobic and aerobic bioreactors. This treated water can be used to ferti-irrigation or heating, coming into heat exchanger with a mass flow of 2 kg/s at 25 °C, coming out with a mass flow of 85 kg/h (0.024 kg/s) at 60 °C. Dairy from 8 h to 18 h, the effluent demand varies for each hour, such as: 15%, 10%, 5%, 5%, 25%, 15%, 10%, 5%, 5% and 5%. These periods are related to classes' hours [86].

A sort of assumptions must be considered. There are a several values considered for evaluations: 22,000 kJ/Nm^3 (28,500 kJ/kg) for biogas lower heating value (LHV), 1.005 kJ/kg K for air specific heat at constant pressure, 1.094 kJ/kg K for exhaust gases specific heat at constant pressure [11], 0.001003 m^3/kg for water specific volume at 25 °C [87], and 1,316.6 kcal/kg (5,477.056 kJ/kg) for biofertilizer LHV based on food waste [88]. Biofertilizer is considered with 40% of humidity in this work [6].

3. Results

The first step is to measure $\dot{m}_{tw}$. It was done using a polypropylene beaker with a linear scale of 1.1 L as span and a chronometer to

watch time spent to fill 1 L. This procedure was repeated ten times then a simple media was calculated to establish a value representative of this mass flow, for both conditions mentioned, with about 15% of uncertainty, because values for equipments degree of accuracy.

After that, the value obtained was converted to the international system unit adopted. With these values, $\dot{m}_{bg}$ and $\dot{m}_{bf}$ are estimated according to [88].

The $\dot{W}_{G_{\max}}$ was established as maximum power generated by internal combustion engine converted to use biogas, tested for the same composition of SWWTP biogas (0.6% of O_2, 2.4% of N_2, 40% of CO_2, 54% of CH_4 and 3% of H_2S [2]) and measured with a wattmeter.

For $\dot{W}_{G_{\max}}$ is not need to buy power from public grid ($\dot{W}_{net}$). In the minimal case ($\dot{W}_G = 1.65$ kW), the same value is bought from power grid, according to conditions established previously.

The ex_{bg} and ex_{bf} are considered as their own LHV [87,88], and ex_{tw} and ex_{sewer} are evaluated through a CATT3 software [87].

Table 1 relates values measured and evaluated for energy self-sufficiency condition for SWWTP (column Max) and values established for a 50% of energy self-sufficiency condition, with 50% of energy demand purchased (column Min).

Based on an extended thermoeconomic model of cogeneration plant developed by [76] and modified by [74,75] with two criteria which need to be minimised, two new equations representative of the thermodynamic criterion (K_{th}) as a deviation of the exergetic efficiency of the SWWTP from an ideal value (the non-dimensional closing error of the system exergy balance) and the economic criterion (K_{ec}) as the total cost rate of operation (the running cost) are adapted for SWWTP costs, according to cost-based structure for SWWTP, Fig. 5, Eqs. (1) and (2).

$$K_{th}(X) = 1 - \frac{\dot{W}_{net} + \dot{m}_{tw}(ex_{tw} - ex_{sewer}) + \dot{m}_{bf}(ex_{bf} - ex_{sewer}) + \dot{W}_G}{\dot{m}_{bg} ex_{bg}} \tag{1}$$

$$K_{ec}(X) = \dot{C}_{bg} + \dot{C}_{el} + \dot{C}_{bf} + \dot{C}_{tw} \tag{2}$$

For (1) and (2), $\dot{W}_{net}$ is a public electrical power grid, $\dot{m}_{tw(bf,bg)}$ is a treated water (biofertilizer, biogas) mass flow rate, $ex_{tw(bf,bg,sewer)}$ is a treated water (biofertilizer, biogas, and sewer) specific exergy, and $\dot{W}_G$ is electrical power generated by the system.

For calculation of costs associated to SWWTP products some analysis conditions are established: interest rate of 4%, 8%, 12%,

Table 1
Thermodynamic features for thermodynamic criterion evaluation.

	Min	Max
$\dot{m}_{bg}$ [kg/s]	0.000837325	0.00167465
$\dot{m}_{tw}$ [kg/s]	0.007199025	0.01439805
$\dot{m}_{bf}$ [kg/s]	0.000001365	0.00000273
$\dot{W}_{net}$ [kW]	1.65	0
$\dot{W}_G$ [kW]	1.65	3.3
ex_{bg} [kJ/kg]	28,500	28,500
ex_{tw} [kJ/kg]	104.8	104.8
ex_{bf} [kJ/kg]	5,477.06	5,477.06
ex_{sewer} [kJ/kg]	104.8	104.8

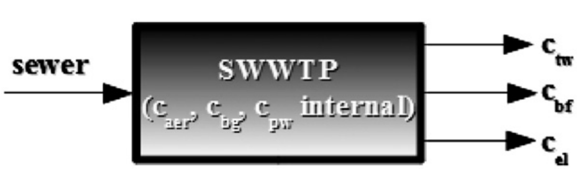

Fig. 5. Cost-based structure [1,3,4].

Table 2
Economic criteria for basic conditions < none > . < /none >

r (%py)	$K_{ec}^{\min}$	$K_{ec}^{\max}$
4	0.188	0.572
8	0.212	0.600
12	0.238	0.630
16	0.267	0.659

and 16% per year and payback periods of 2, 4, 6, 8, and 10 years [3,4]. From these conditions associated to values evaluated in previous analysis [3,4], economic criteria is calculated, such as related in Table 2.

These values (Table 2) are applied to matrix table [T] to obtain boundary conditions for economic criteria evaluation.

The definition of the decision variable X (x_1 = sewer), physical constraints, and the purchase cost functions for each plant component are taken from work of Lamas et al. [1–4,86].

Fuzzification of the goals leads to the following membership functions:

$$\mu_{K_{th}}(X) = \begin{cases} 0, & \text{if} \quad K_{th}(X) > K_{th}^{\max} \\ \frac{K_{th}^{\max} - K_{th}(X)}{K_{th}^{\max} - K_{th}^{\min}} & \text{if} \quad K_{th}^{\min} < K_{th}(X) \le K_{th}^{\max} \\ 1, & \text{if} \quad K_{th}(X) \le K_{th}^{\min} \end{cases} \tag{3}$$

$$\mu_{K_{ec}}(X) = \begin{cases} 0, & \text{if} \quad K_{ec}(X) > K_{ec}^{\max} \\ \frac{K_{ec}^{\max} - K_{ec}(X)}{K_{ec}^{\max} - K_{ec}^{\min}} & \text{if} \quad K_{ec}^{\min} < K_{ec}(X) \le K_{ec}^{\max}, \\ 1, & \text{if} \quad K_{ec}(X) \le K_{ec}^{\min} \end{cases} \tag{4}$$

where matrix table [T] is defined as:

$$[T] = \begin{pmatrix} K_{th}^{\min}(X) = 0.861 & K_{th}^{\max}(X) = 0.931 \\ K_{ec}^{\max}(X) = 0.572\,\frac{US\$}{h} & K_{ec}^{\min}(X) = 0.188\,\frac{US\$}{h} \end{pmatrix}. \tag{5}$$

Fig. 6 shows a Pareto set evaluated for conditions presented by (5), with economic criterion values for 4% per year of interest rate, as viewed in Table 2.

For the conditions related, thermodynamic criterion and economic criterion values meet themselves near to exergetic efficiency (K_{th}) of 0.89 for 4 kWh of electrical power generated and operation cost (K_{ec}) of 0.375 US$/h for 20 kg/h of sewage flow mass, which show that these conditions are the best ones for this system. It is because the SWWTP had been design throughout thermoeconomic criterion applied to it.

4. Conclusions

These simulations can confirm that the modelling proposed is representative for the small waste water treatment plant at UNESP-Guaratingueta. Conditions of constant sewage flow are compared to multi-period variation of sewage flow. This comparison showed that a fuzzy set control is a good way to maintain small waste water treatment plant producing the best amount of its products, including biogas and electrical power to its energy self-sufficiency, with a positive influence in heat exchangers warmth. The exergetic production cost also had a good performance in these simulations, turning around 0.20–0.65 US$/h to a biogas flow of 1.47 kg/s.

Results deal to previous system optimisation that was a physical optimisation through a thermoeconomic analysis. Then, Pareto set for this one was validated by the previously system optimisation and had confirmed that it is working with better configuration for E_P = 4 kWh and $\dot{m}_s$ = 20 kg/h.

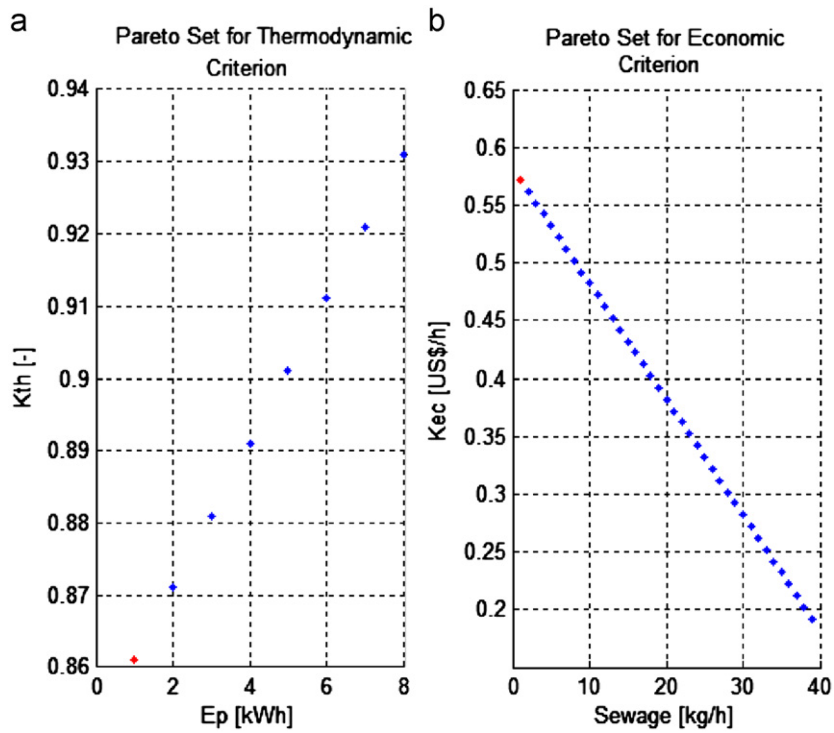

Fig. 6. Pareto set.

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